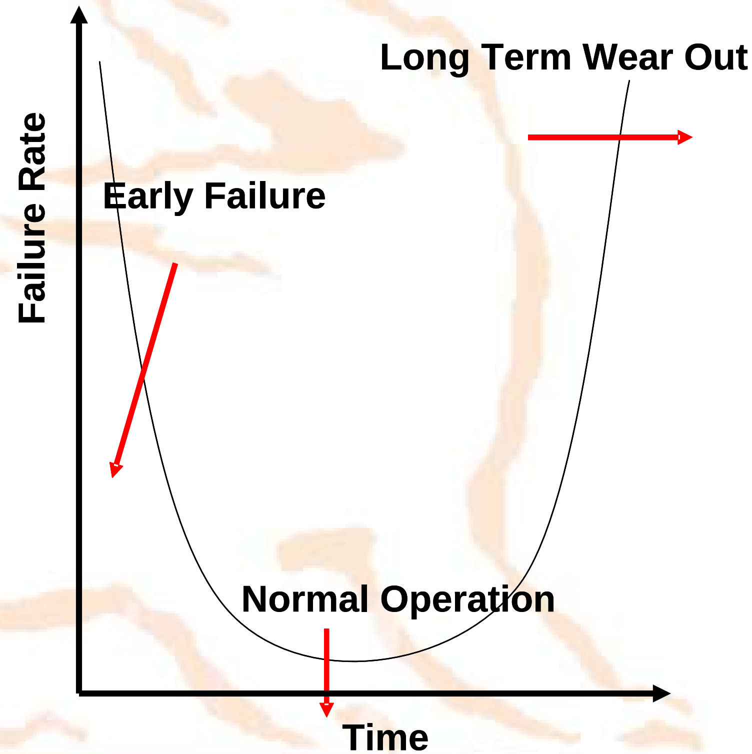
Thrust 3: Electrical Characterization Overview/ Effect of Strain on Trap-related Reliability Mechanisms

T. Nishida, S. Thompson, G. Bosman
Department of Electrical and Computer Engineering

March 16, 2009

Overview

- Goal
  - Employ multiple characterization vectors
  - Gain insight into physical degradation mechanisms
  - Feedback into predictive models
  - Compare predictions with characterization results



Outline

- Fundamental reliability mechanisms (traps)
- Strain in as fabricated devices + inverse piezoelectric strain
- Approach: Characterization as function of systematically applied strain
- Simulation of strain effects on traps and reliability
- Summary

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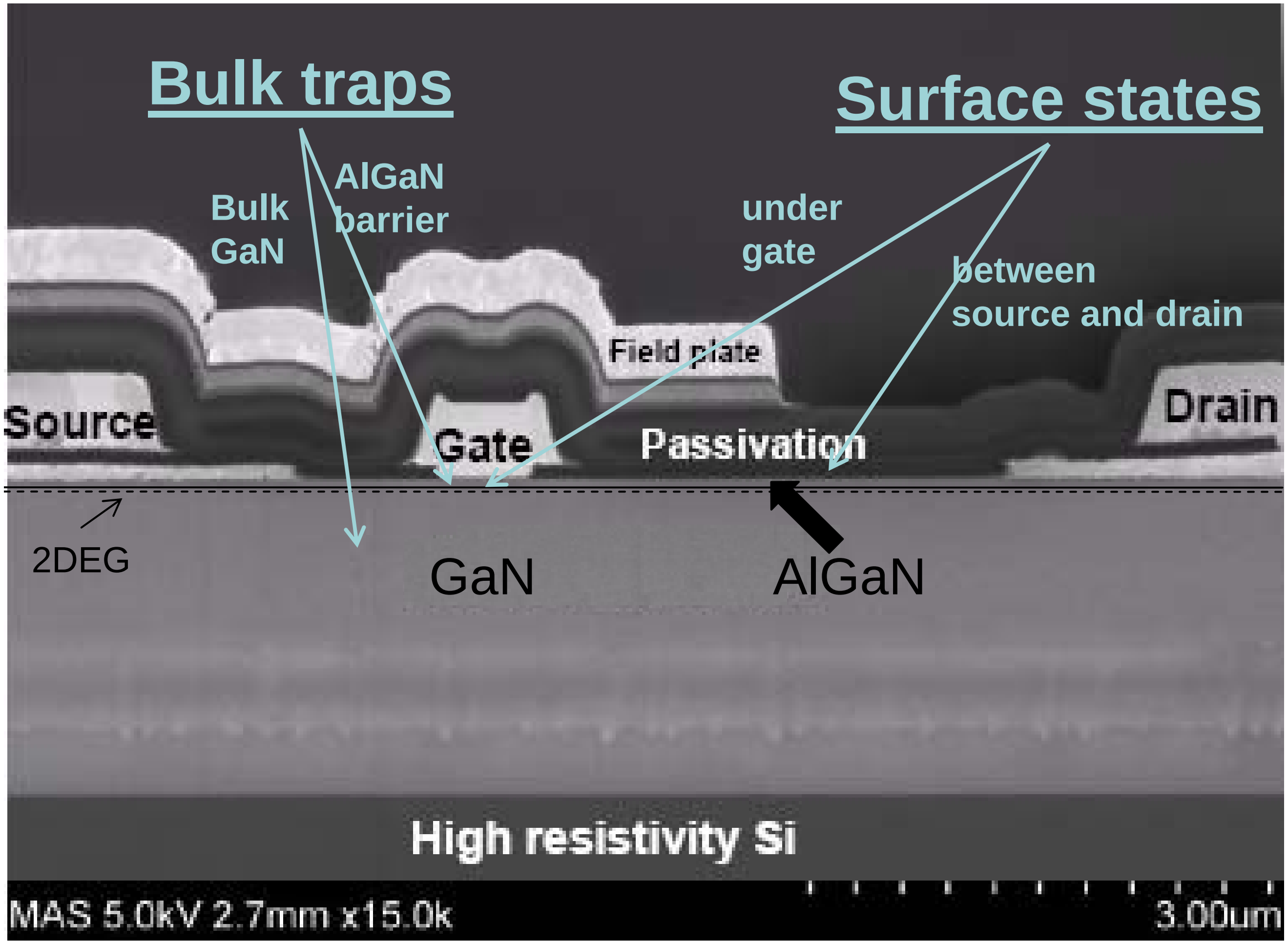
GaN HEMT Reliability Issues-Cause & Effect



Cause

- growth-*as fabricated* traps
- post-growth process *as fabricated* traps
- hot-carrier injection *generated* traps
- inverse piezoelectric strain *generated* traps

Effect

- current collapse
- gate-lag
- drain-lag
- ΔV_T
- increased I_G
- light sensitivity
- breakdown

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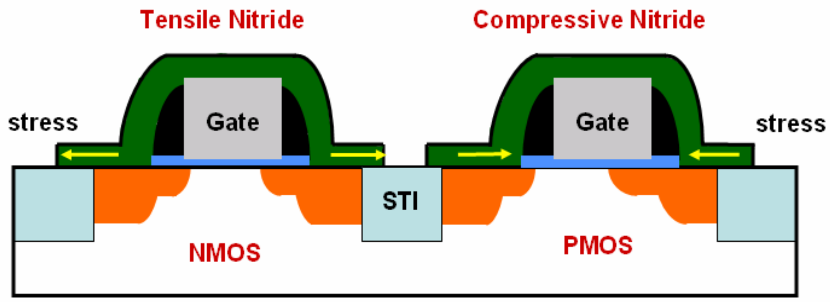
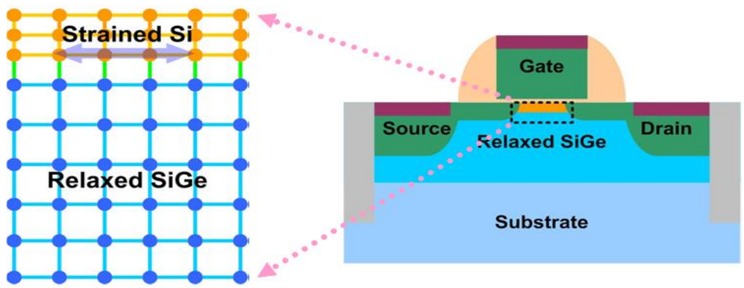
As Fabricated Modern Si Devices

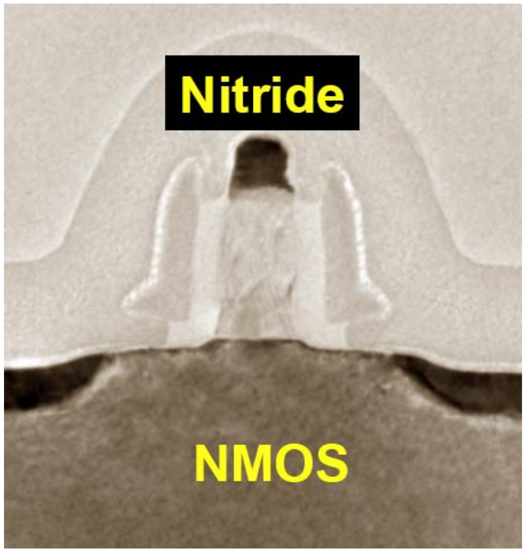
Uniaxial Stress

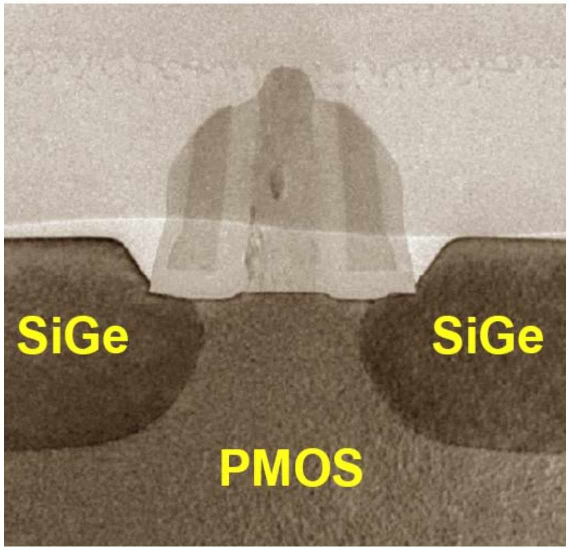


Biaxial Stress

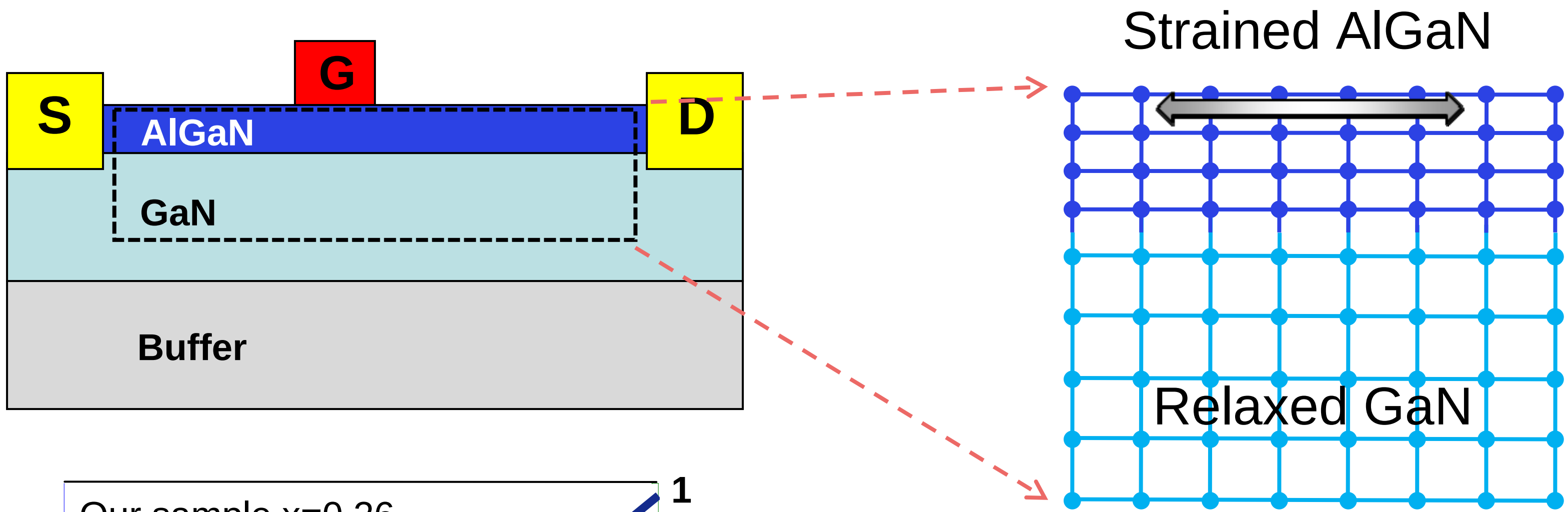


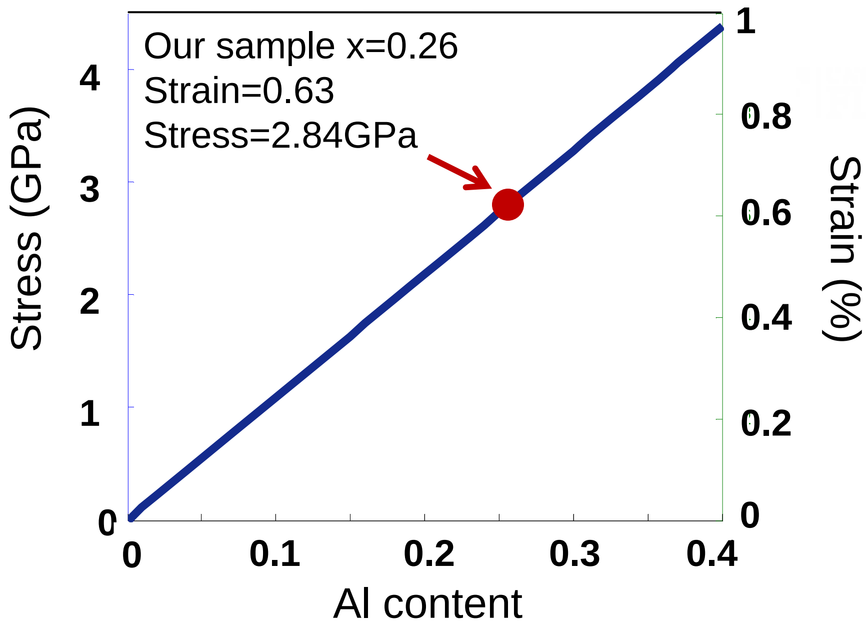
Over 1GPa built-in stress has been achieved in Si MOSFETs, with the main purpose to enhance drive current.





As Fabricated GaN HEMT: Lattice Mismatch





$$a_{GaN} = 3.189\ \overset{o}{A} \qquad a_{AlN} = 3.112\ \overset{o}{A}$$

$$a_{Al_xGa_{1-x}N} = 3.189 \times (1 - x) + 3.112 \times x$$

$$\varepsilon_{Al_xGa_{1-x}N} = \frac{a_{GaN} - a_{Al_xGa_{1-x}N}}{a_{Al_xGa_{1-x}N}}$$

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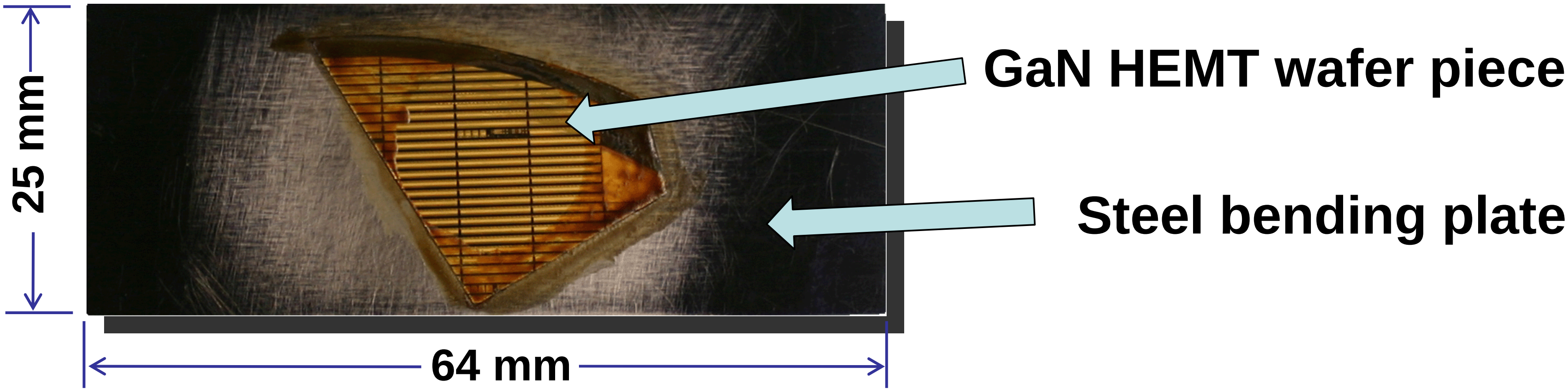
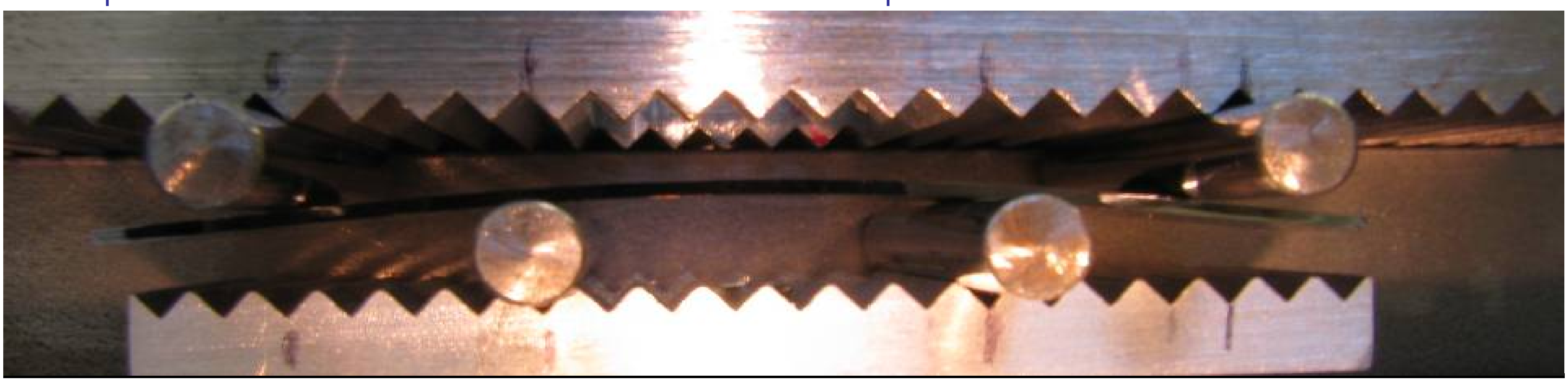
Strain Setup for GaN Commercial HEMT

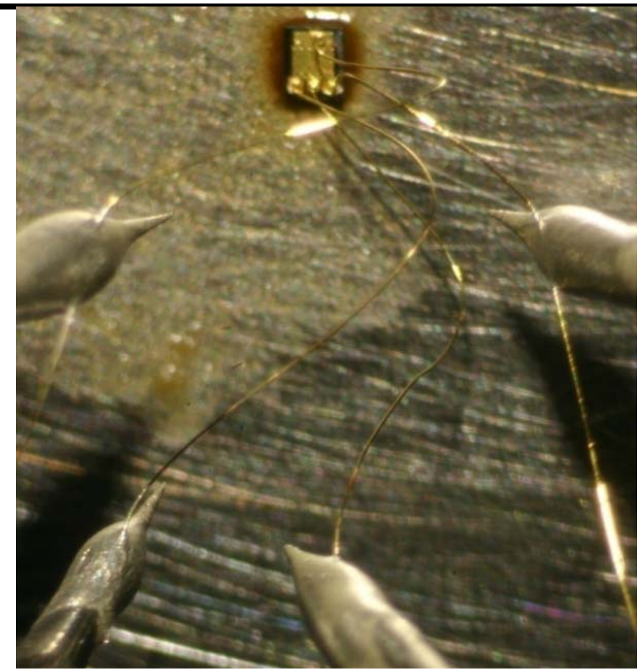
- GaN HEMT wafer samples too small to directly bend in 4-point bending setup
- Solution: (1) epoxy GaN HEMT wafer sample on high carbon stainless steel
  (2)calibrate achieved strain by strain gauge measurements





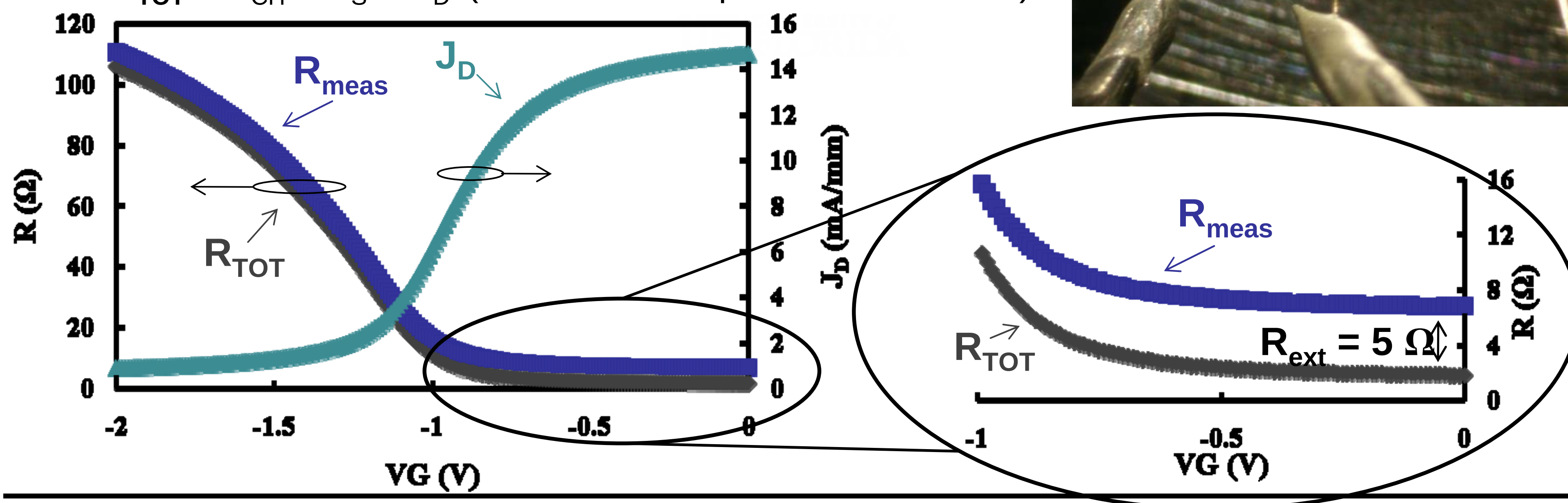
Strain Setup Measurement Technique

- Strain setup requires wire-bond to pads
  - Four-point measurement isolates channel resistance since R_{ext} comparable to R_{TOT}
    - Wide commercial device → small channel resistance
    - Wire-bonding and epoxy → large external resistance

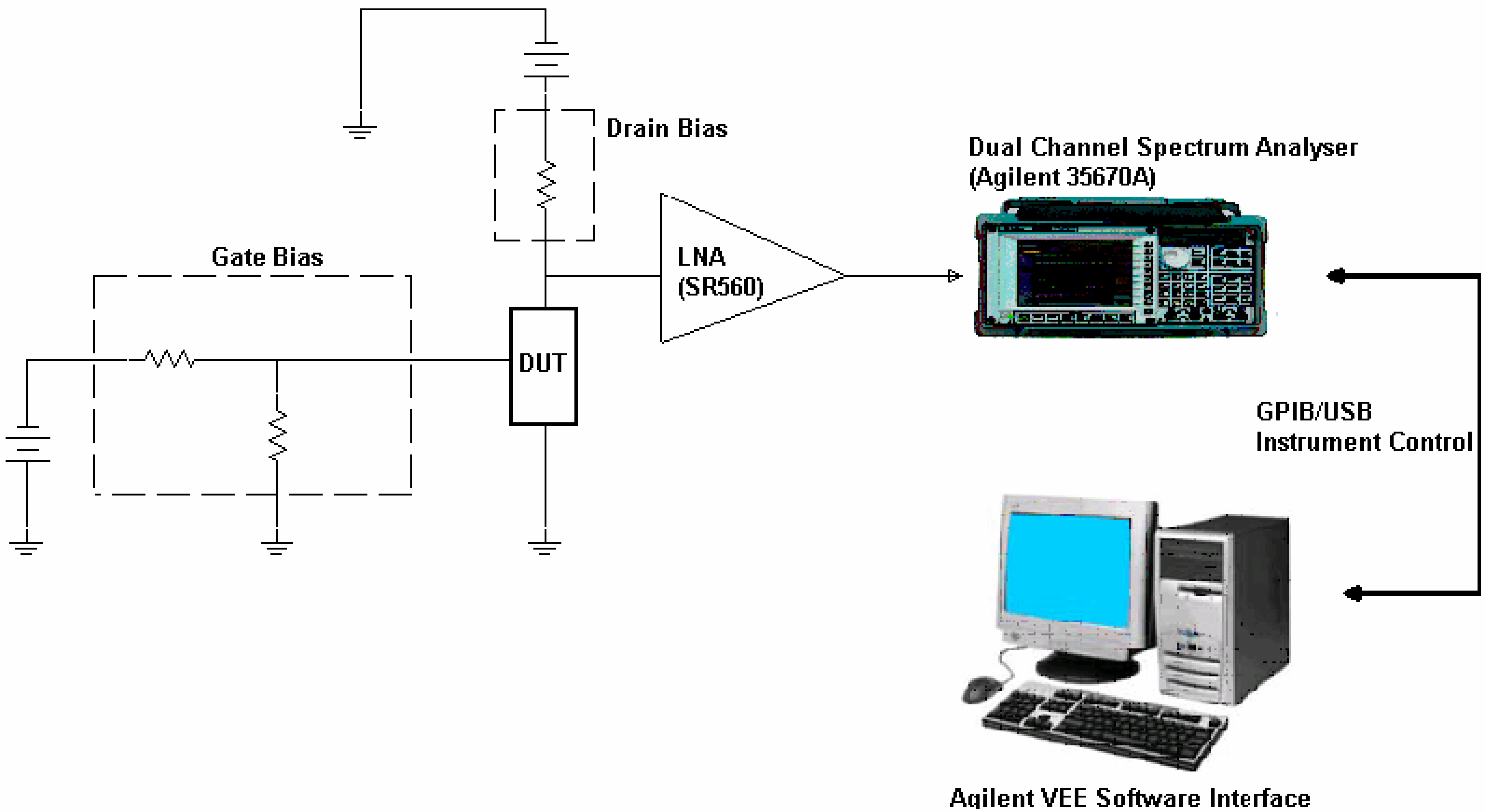


$\mathbf{R_{meas}} = V_{DS} / I_D = R_{TOT} + R_{ext}$

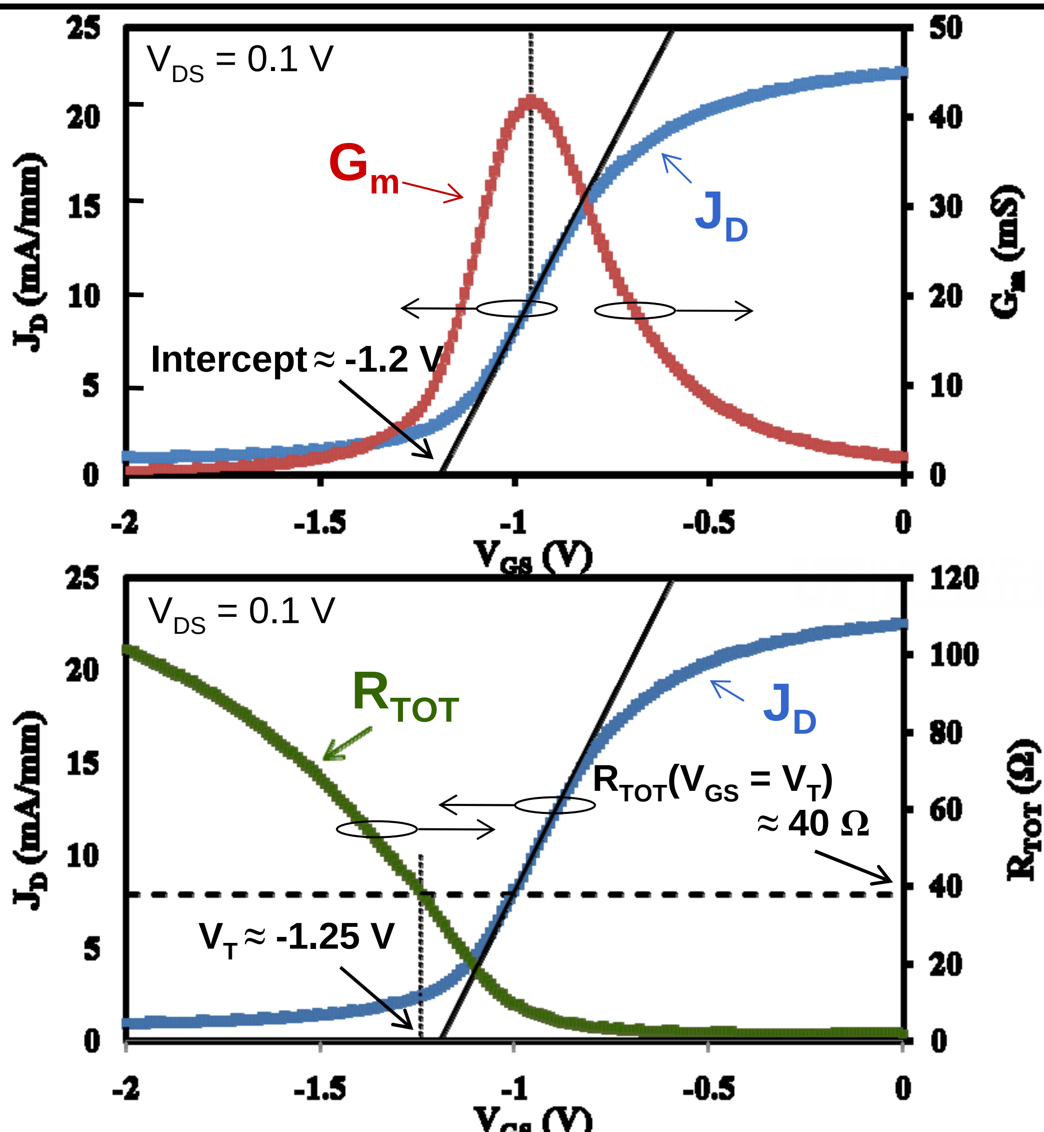
$\mathbf{R_{TOT}} = R_{CH} + R_S + R_D$ (extracted via 4-point measurement)



Noise Measurement Setup



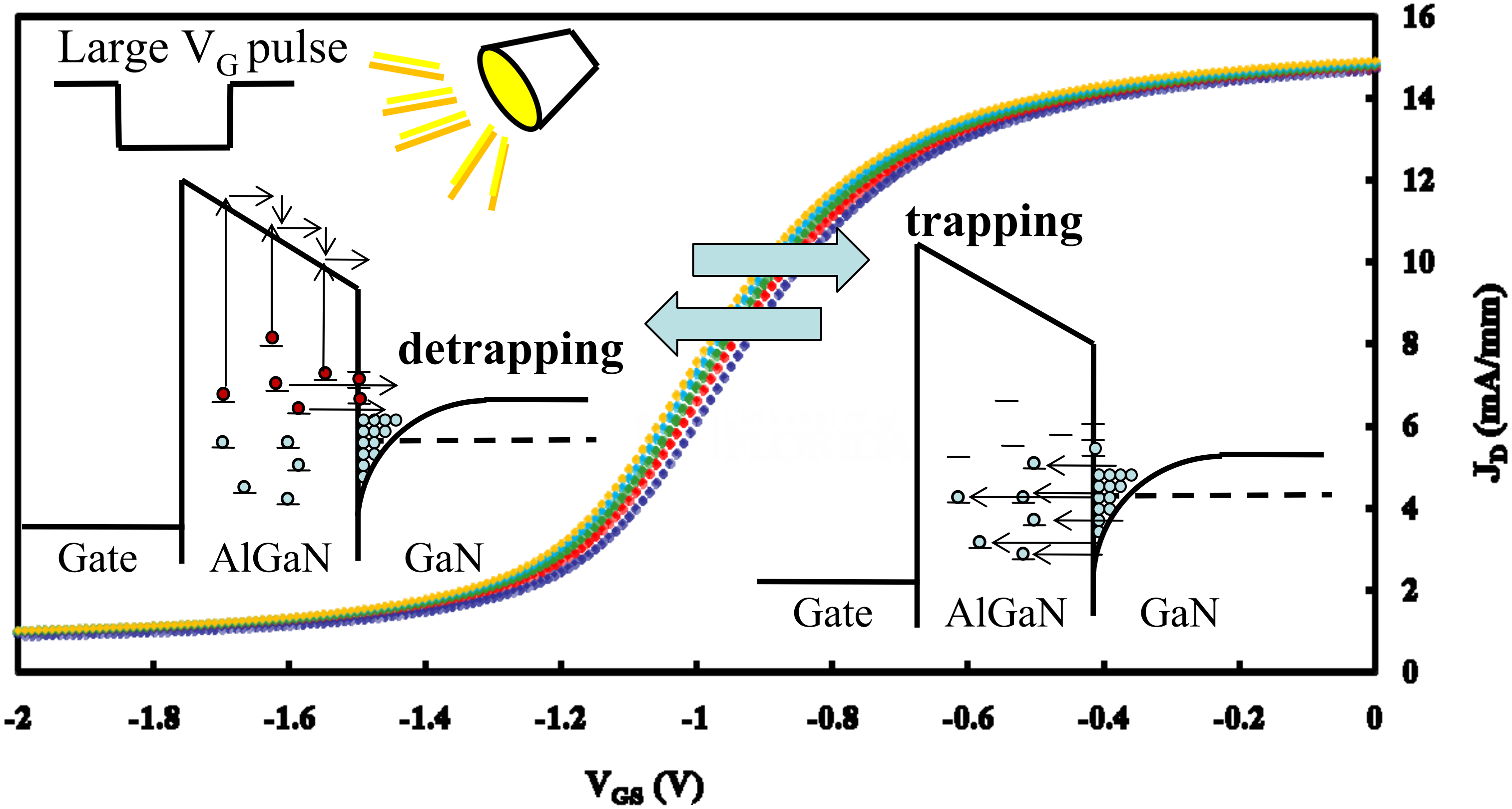
V_T Measurements



1. Linear extrapolation of intercept
   - Effect of R_{ext}
2. Constant R_{TOT}
   - 4-point measurement removes effect of R_{ext}
   - V_T defined as R_{TOT} for V_{GS} = intercept – $mV_{DS}/2$; m = $1+C_d/C_{ox}$ ~ 1 ideal case [Y. Taur, Fundamentals of VLSI Decices]

Single Device Stability

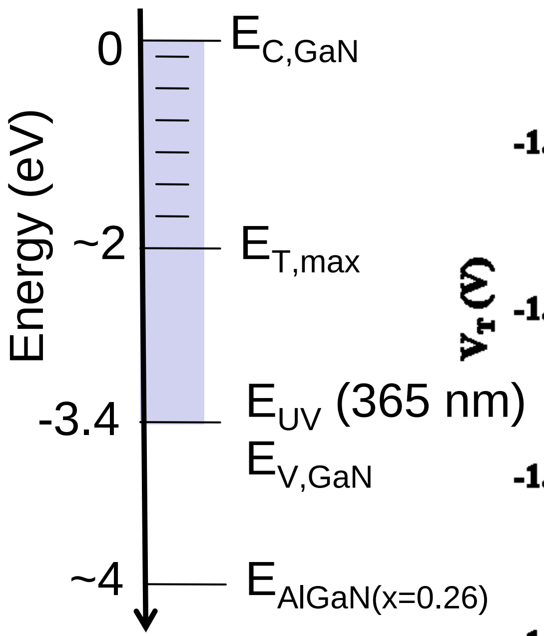
Consecutive V_{GS} = -2 to 0 V_{DS} = 0.1 V measurements

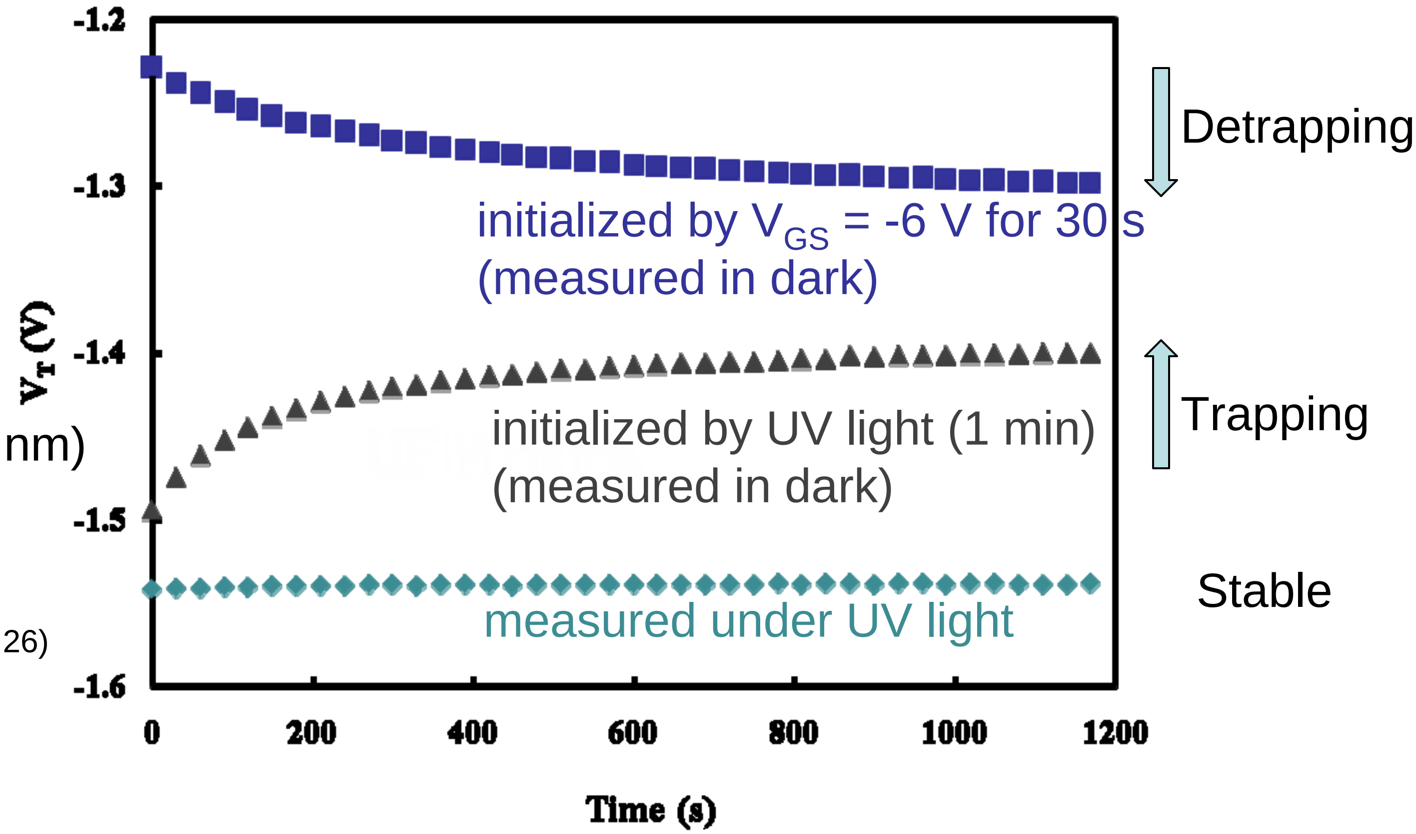


Measurements and exposure to light result in drift due to electron trapping and detrapping

Various Options to Stabilize Device

Consecutive V_{GS} = -2 to 0 V_{DS} = 0.1 V measurements

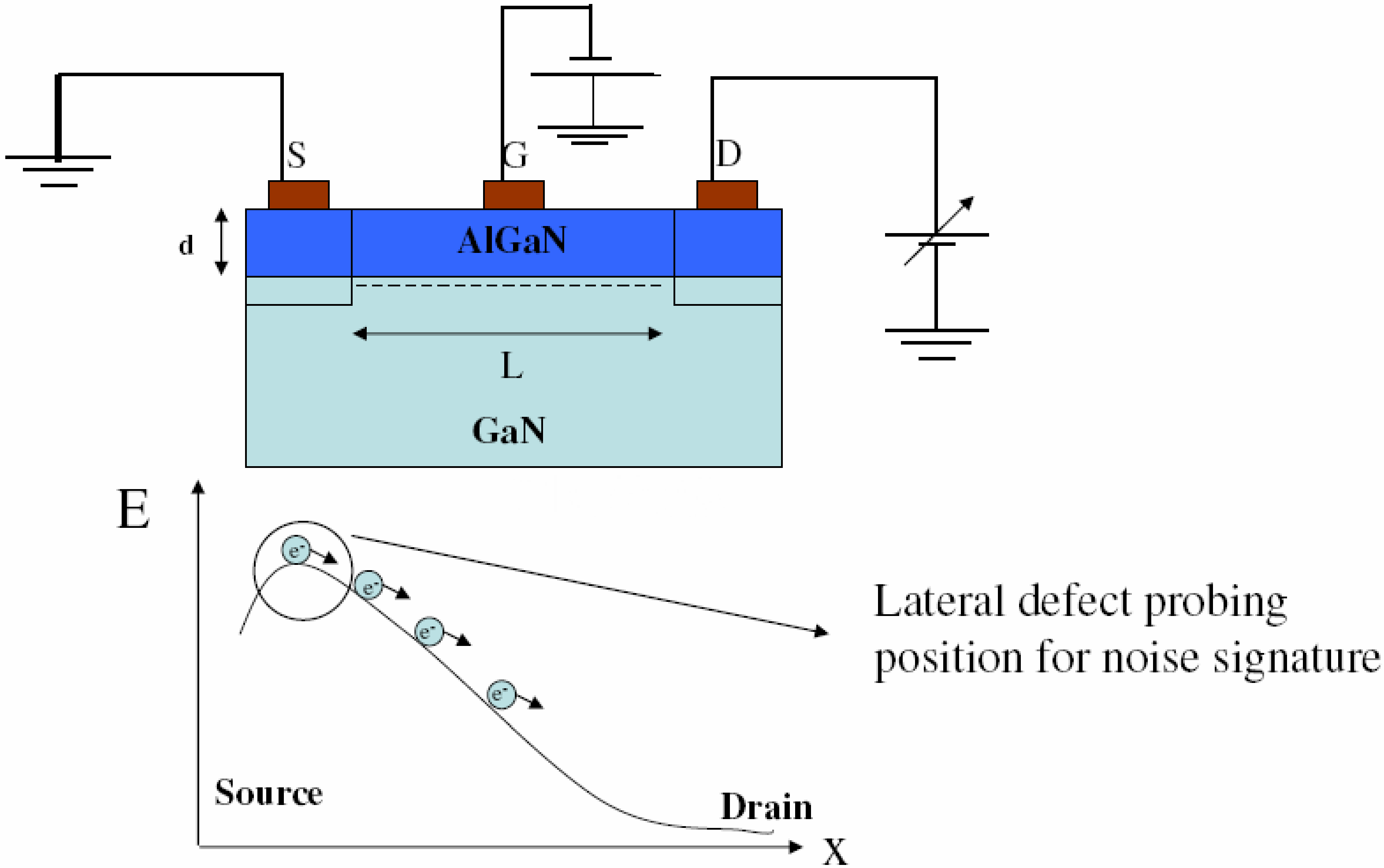




UV light detraps most trapped electrons

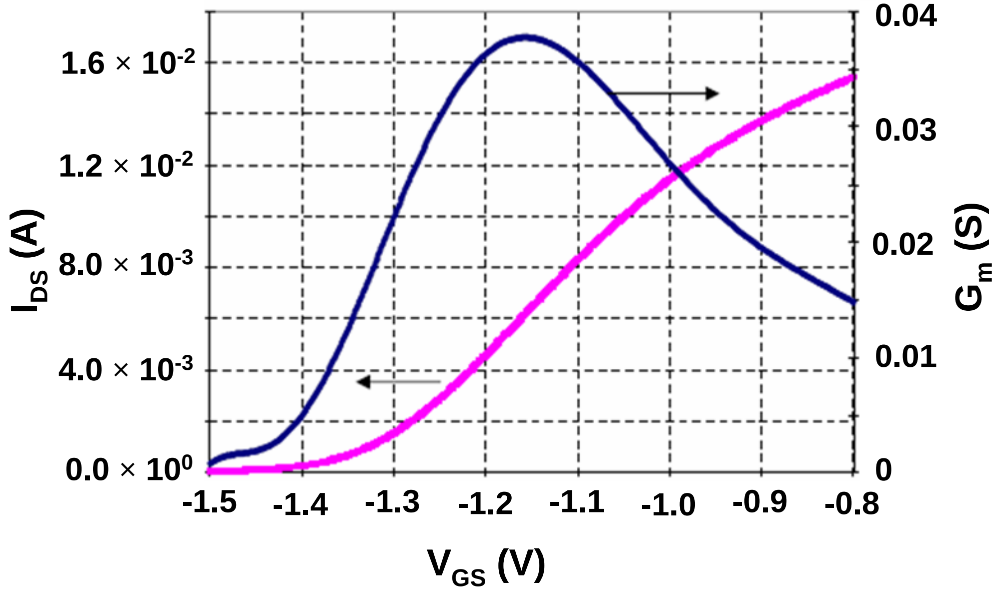
UV light can used as a tool to stabilize measurements and study traps

Lateral Defect Probing: Switched S/D Noise

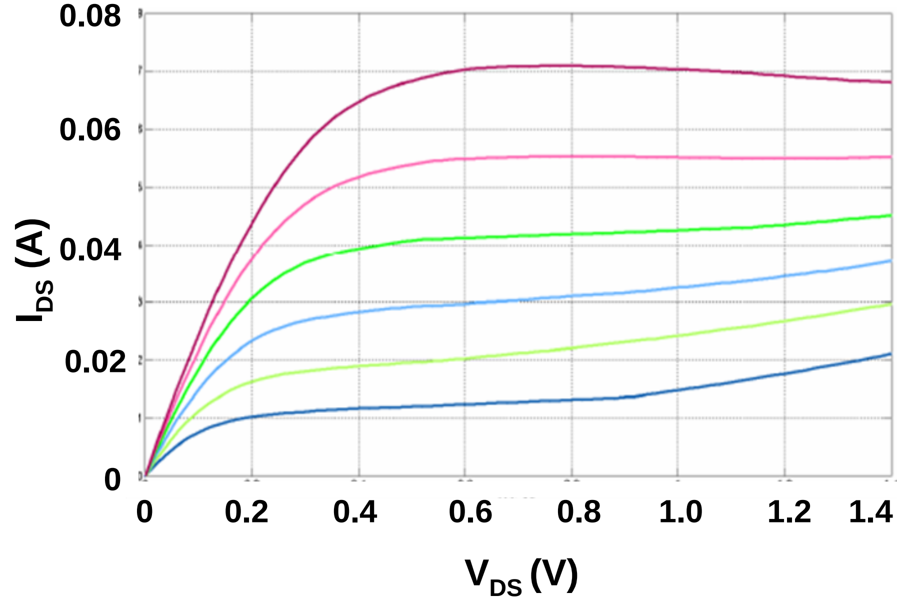


DC Characteristics of GaN HEMT

Transconductance (V_{DS}=0.05V)



I_{DS} vs V_{DS}



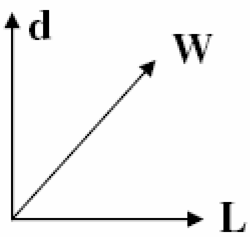
Vg = -1.20 to -0.95 V (Step 0.5 V)

Vds = 0 to 1.4 V

Extraction of effective mobility using $\frac{I_{DS}}{\sqrt{g_m}} = \left(\frac{W\varepsilon_{AlGaN}\mu_0 V_D}{Ld_{AlGaN}}\right)(V_g - V_t)$

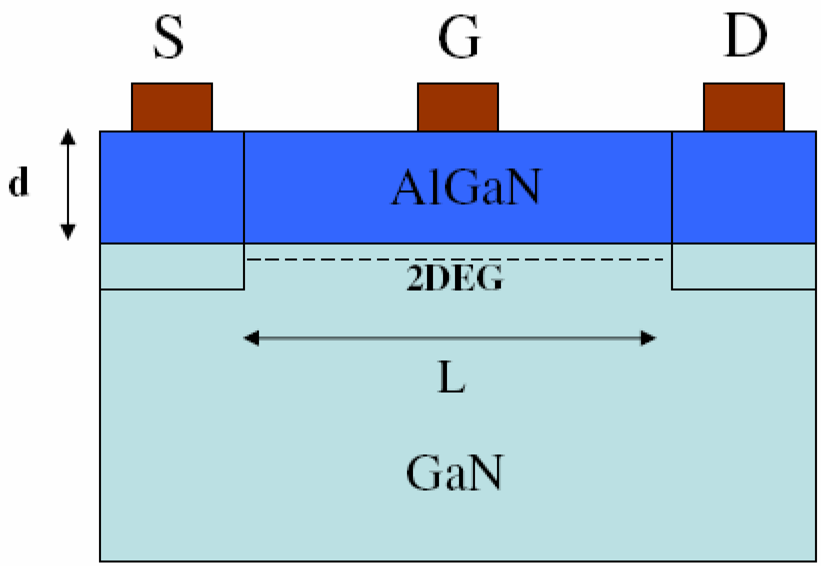
Ref. Ghibaudo (1988)

Approximate DC Parameter Extraction



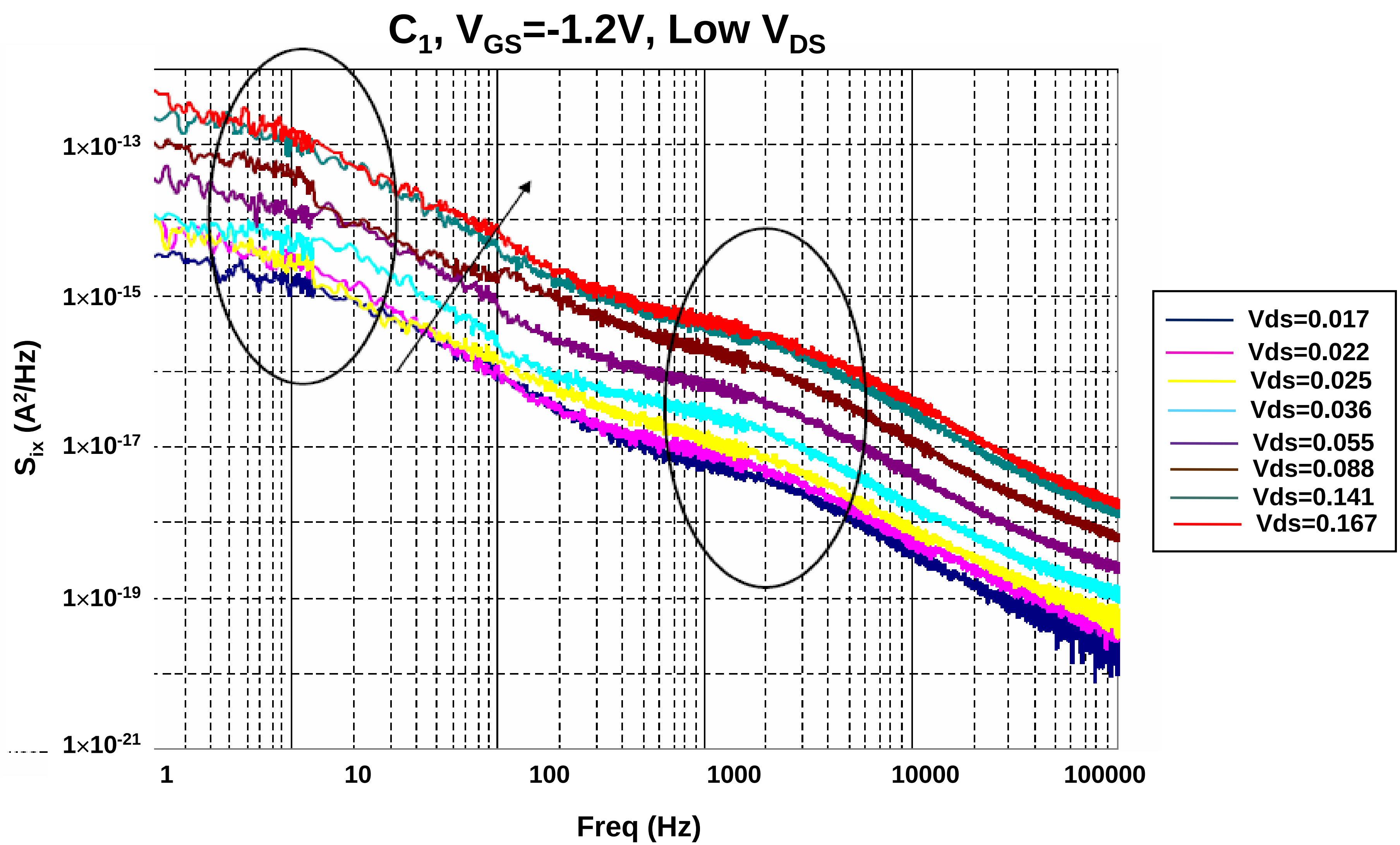
$$I_D = \frac{qW\mu}{L}\left(n_{so}V_D - \frac{\varepsilon_{AlGaN}}{2qd_{AlGaN}}V_D^2\right)$$

$$\mu_{FE} = \frac{Lg_m d_{AlGaN}}{W\varepsilon_{AlGaN}V_{DS}}$$

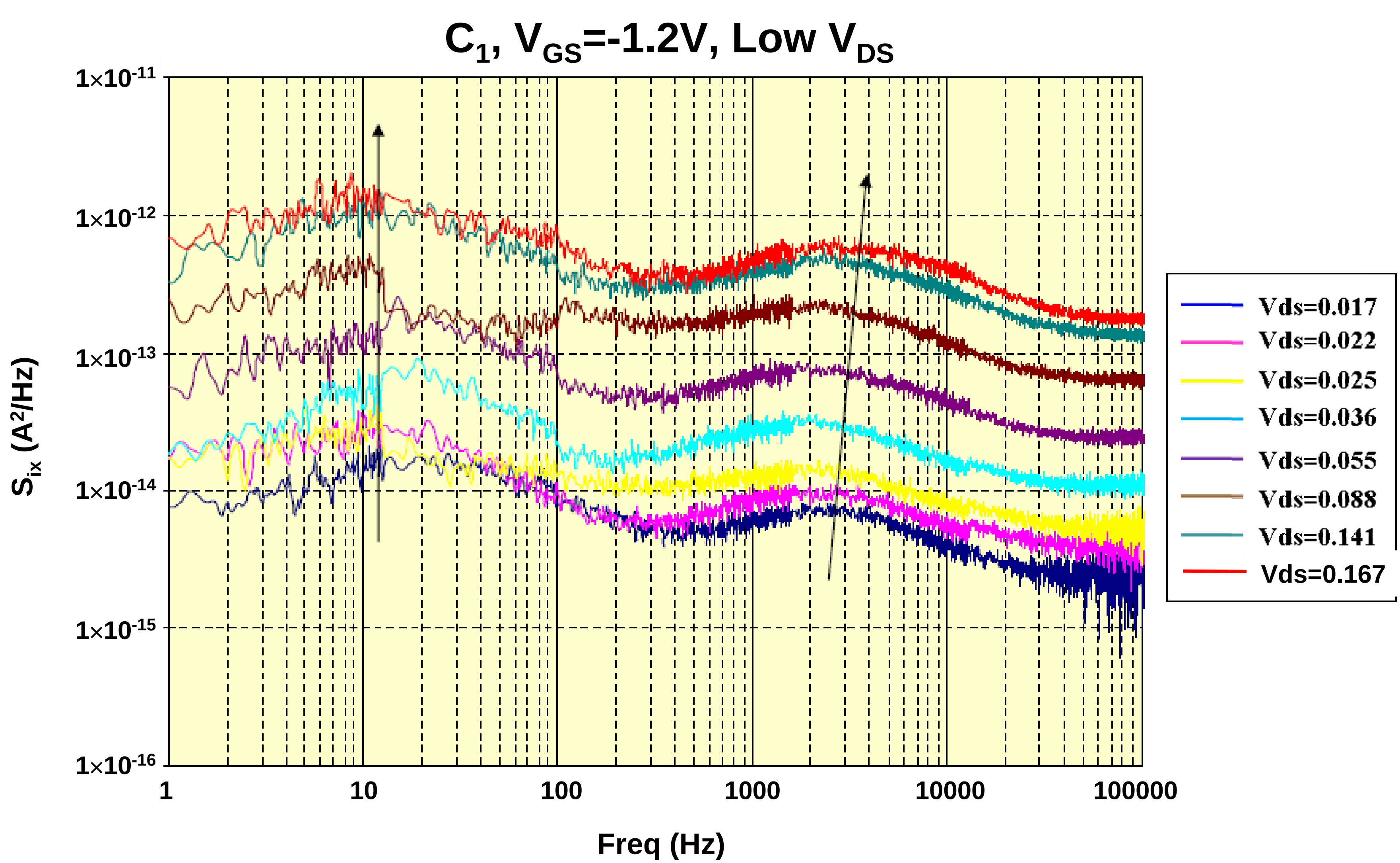


- Channel Length (L) ~ 3.7 μm
- Channel Width (W) ~ 202 μm
- Low Field Mobility (μ_{FE}) ~ 1535 $cm^2/V.s$
- Gate fingers (N) ~ 14
- V_t ~ -1.40 V
- AlGaN Layer thickness (d) ~ 17.3 nm

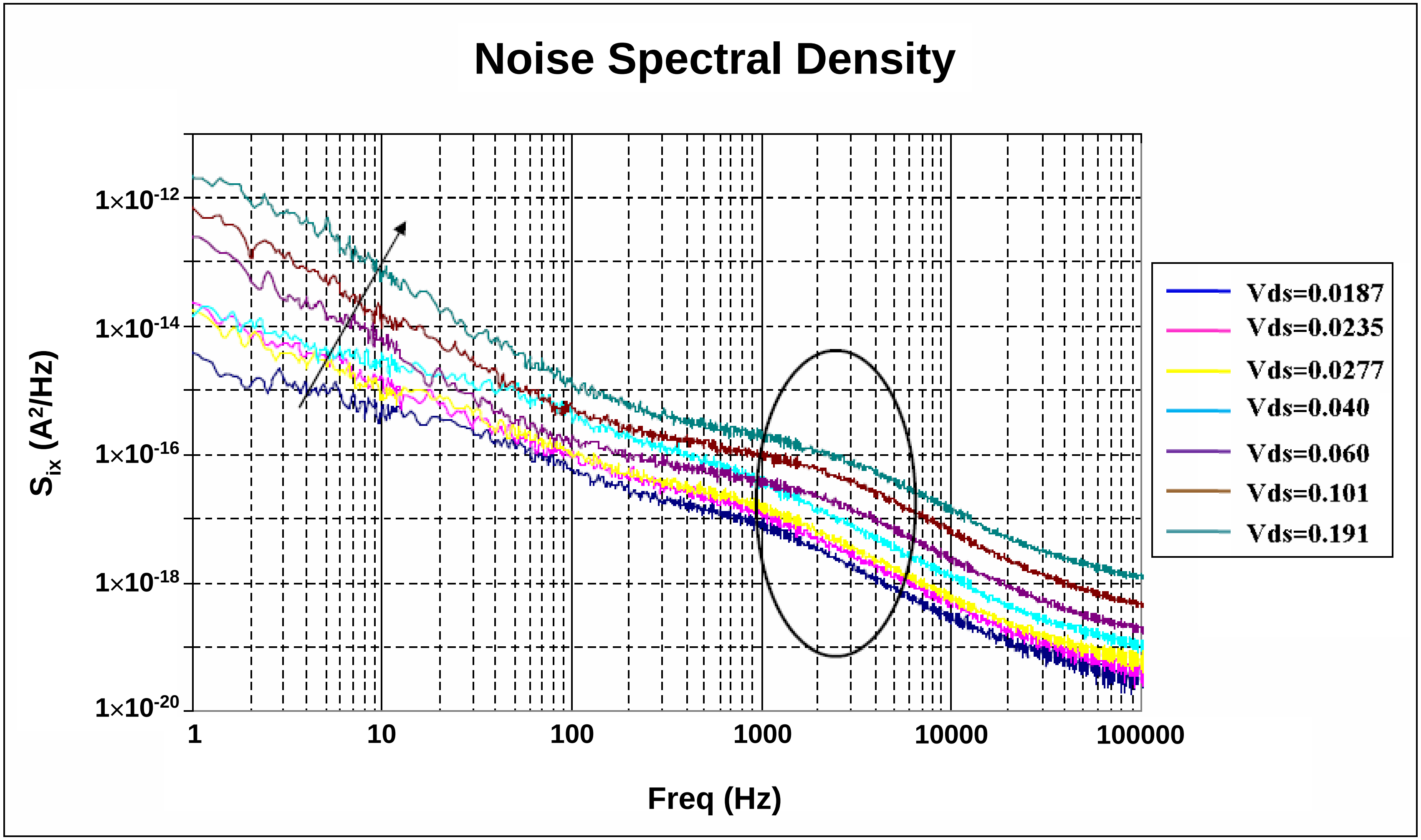
Forward Drain Noise Data (S_{id}) GaN HEMT



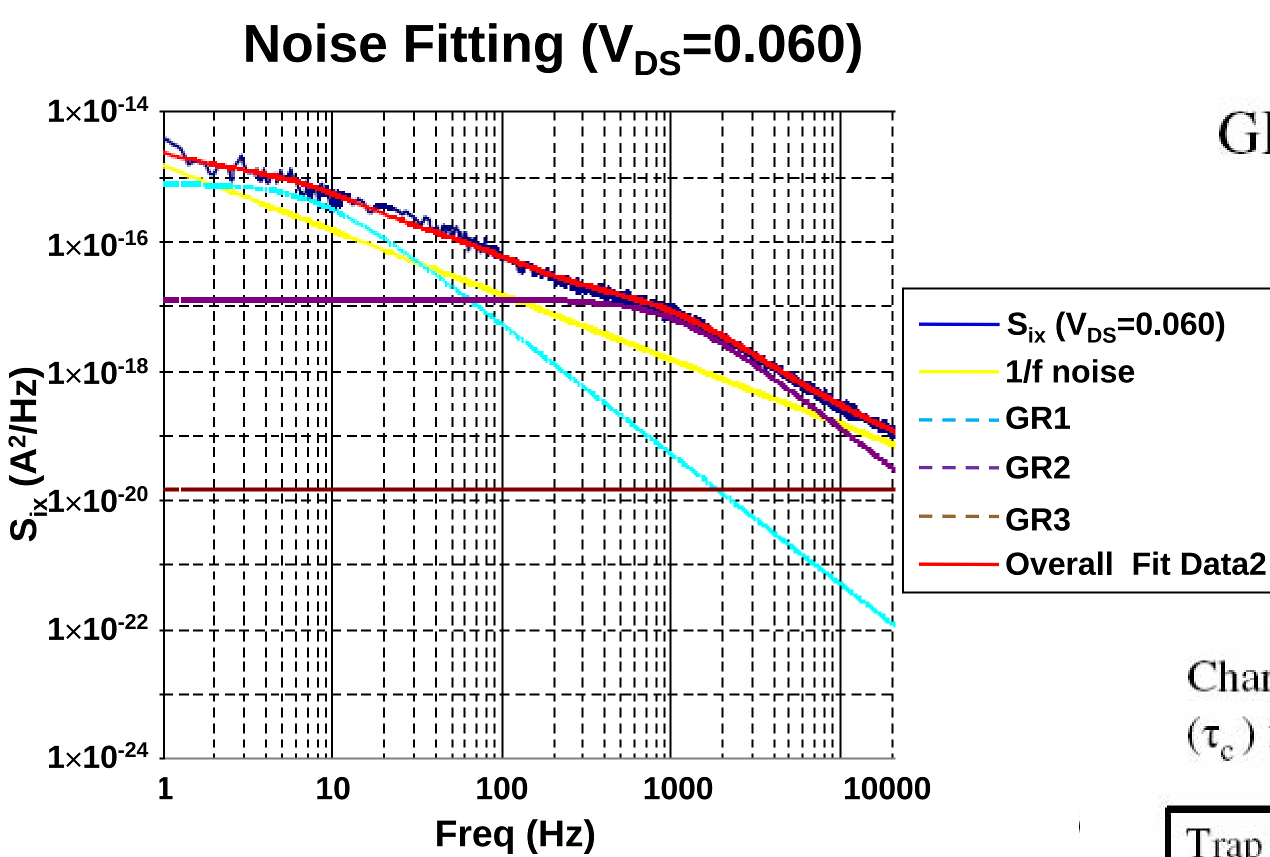
Forward Drain Noise Data ($S_{id} \times f$)



Reverse Drain Noise Data (S_{id}) GaN HEMT



Noise Decomposition Normal S-D Operation



GR Noise and 1/f Noise

$$S_{ID}(f) = \frac{q\mu\alpha_H I_D V_{DS}}{L^2 f}$$

Approximate Hooge Parameter $\alpha_H = 2.56\times10^{-3}$

Characteristic Relaxation Time (τ_c) for GR Noise

Trap 1	Trap 2	Trap 3
14.4 ms	132.7 μs	1.06 μs

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Simulation Capability—Band Structure

—Tight binding method.

✓ relatively simple and gives whole band structure
✓ straightforward microscopic picture of how strain affects inter-atomic interactions

—k·p method.

✓semi-empirical parameters for greater accuracy at the Γ point
✓physical parameters such as momentum-matrix elements and eigen-energies
✓ strain effect incorporated through **deformation potential**

k·p method used since semi-empirical and more accurate

- effective mass
- mobility enhancement
- threshold voltage shift
- gate leakage change

[Opt Quant Electron, vol. 40, pp. 295, 2008]

k·p Method for Wurtzite Crystal

The Hamiltonian $$H = H_0 + \frac{\hbar^2 k^2}{2m_0} + H_{so} + \frac{\hbar}{m_0} k \bullet p + H_{strain}$$

Conduction and valence bands Hamiltonian

- Conduction band (parabolic band model) $$H^c(k_t, k_z) = (\frac{\hbar^2}{2})(\frac{k_t^2}{m_e^t} + \frac{k_z^2}{m_e^z}) + E_c + H_{strain}$$

- Valence band $$H_{6\times6}{}^v(k) = \begin{bmatrix} H_{3\times3}^U(k) & 0 \\ 0 & H_{3\times3}^L(k) \end{bmatrix} + H_{strain}$$

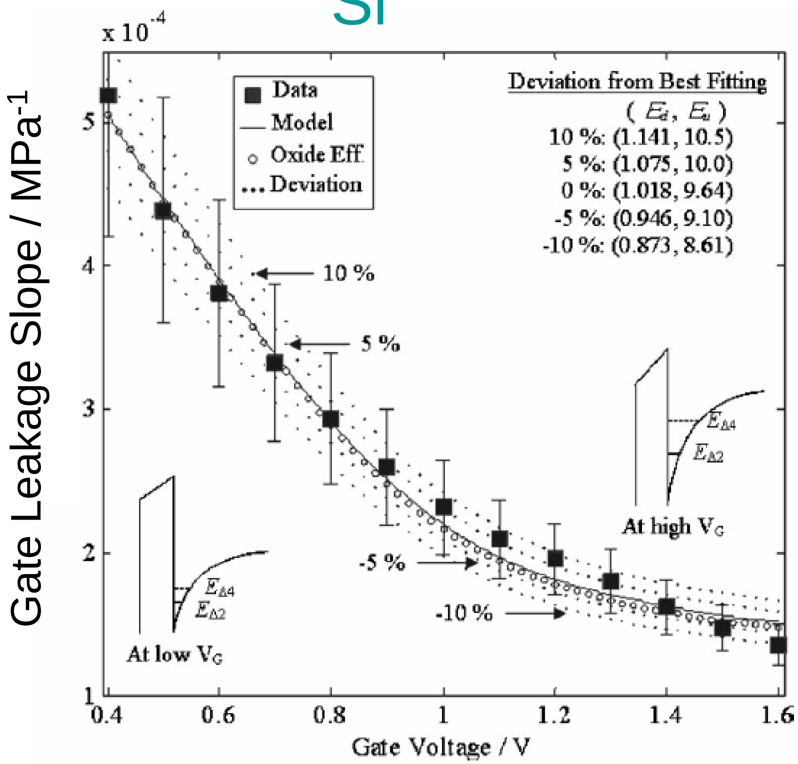
where $$H_{3\times3}^U(k) = \begin{bmatrix} F & K_t & -iH_t \\ K_t & G & \Delta - iH_t \\ iH_t & \Delta + iH_t & \lambda \end{bmatrix}$$ and $$H_{3\times3}^L(k) = conj(H_{3\times3}^U(k))$$

[Phys. Rev. B, 54, 2491 (1996)]

Deformation potential basis to construct the strain Hamiltonian

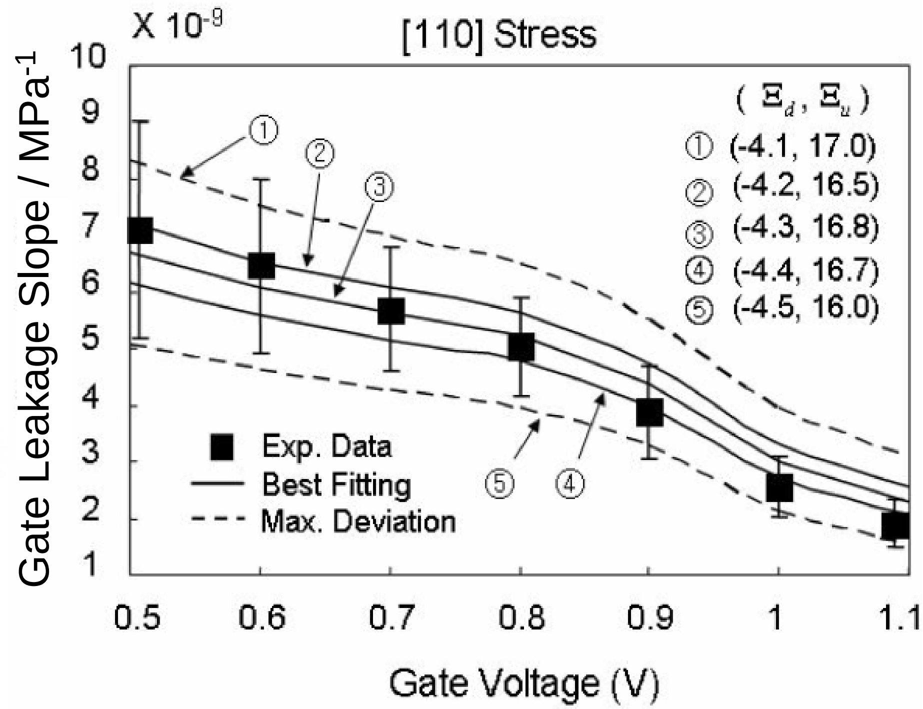
Conduction Band Deformation Potential

Si



[APL, vol. 89, pp. 073509, 2006]

Ge



[JAP, vol. 102, pp. 104507, 2007]

For Si and Ge, accurate Ξ_d and Ξ_u can be extracted from gate leakage measurement. Extract deformation potential for GaN.

Variability of Deformation Potential

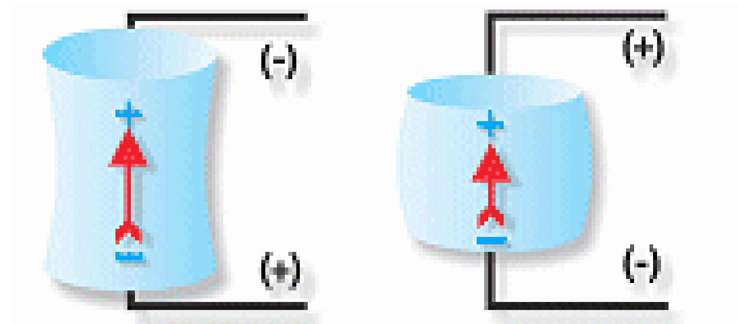
(eV)	Si	Ge
Ξ_d	**1.0±0.1**[c], 1.1[b], 1.2[b], 1.13[b], 5[b],	**-4.3±0.3**[a], -4.43[b], -12.3~-10.5[b], -6.6[b],
Ξ_u	**9.6±1.0**[c], 10.5[b], 8.86[b], 9.2[b], 7.3[b], 9.29[b],	**16.5±0.5**[a], 16.8[b], 11.07[b], 15.13[b], 16.2[b], 15.9~19.3[b],
a	2.1[b], 2.46[b], 2.06[b],	2.0[b], 1.24[b], 2.09[b], -12.7[b], 1.39[b]
b	-2.33[b], -1.5[b], -2.1[b], -2.2[b], -2.12[b], -2.35[b], -2.58[b], -2.27[b]	-2.16[b], -2.1[b], -2.2[b], -2.08[b], -2.5[b], -2.55[b], 2.86[b], -3.11[b]
d	-4.75[b], -3.4[b], -4.85[b], -5.3[b], -3.69[b]	-6.06[b], -3.5[b], -4.4[b], -3.7[b], -4.5[b], -5.3[b], -4.65[b], -7.0[b]

(eV)	GaN
a	-8.16[d], -9.2±1.2[e],
D_1	0.7[d], -20[f], -13.9[f], -41.4[g], -13.87[h]
D_2	2.1[d], -14.2[f], -13.7[f], -33.3[g], -10.95[h]
D_3	1.4[d], 5.80[f], 8.82[f], 7.2[f], 2,99[f], 5.7[f], 6.61[f], 8.2[g], 2.92[h]
D_4	-0.7[d], -3.25[f], -4.41[f], -3.4[f], -3.6[f], -1.63[f], -2.85[f], -3.55[f], -4.1[g], -5.84[h]
D_5	-2.85[f], -3.3[f], -2.04[f], -4.7[g]

[a] [JAP, vol. 102, pp. 104507, 2007]
[b] [JAP, vol. 80, pp. 2234, 1996]
[c] [APL, vol. 89, pp. 073509, 2006]
[d] [PR B, vol. 54, pp. 2491, 1996]
[e] [APL, vol. 66, pp. 3492, 1995]
[f] [JAP, vol. 84, pp. 4951, 1998]
[g] [PR B, vol. 65, 075202, 2002]
[h] [JJAP, vol. 34, pp. L821, 1995]

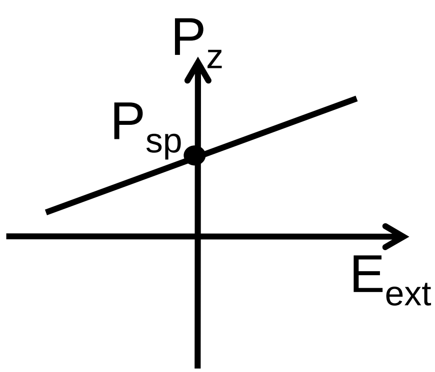
Strain Induced by Inverse Piezoelectricity

Inverse Piezoelectricity: Strain actuated by applied electric field



1) Applied electric field E_{ext}

2) $E_{ext} \longrightarrow$ Polarization P_z



3) P $\longrightarrow$ In-plane strain ε_{xx}

$$\begin{pmatrix} P_x \\ P_y \\ P_z \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 & e_{15} & 0 \\ 0 & 0 & 0 & e_{15} & 0 & 0 \\ e_{31} & e_{31} & e_{33} & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \varepsilon_{yz} \\ \varepsilon_{zx} \\ \varepsilon_{xy} \end{pmatrix}$$

$$\varepsilon_{xx} = \varepsilon_{yy} = \frac{C_{33}}{2\left(e_{31}C_{33} - e_{33}C_{13}\right)} \mathrm{P}_z$$

GaN: $e_{31} = -0.32 \quad e_{33} = 0.63$

AlN: $e_{31} = -0.38 \quad e_{33} = 1.29$

Under typical HEMT operation bias (V_{DG}~20V), additional strain induced by inverse piezoelectricity is around 0.1% (500MPa). **[JAP, vol. 84, pp. 4951, 1998]**

Stress Effect on Hot Carrier Reliability: *Si vs. GaN*

	Si	GaN
E_g	1.12eV	3.4eV
ΔE_g	4% / 1GPa	1.3% / 1GPa
$\Delta\mu$	30% / 1GPa	2% / 1GPa
$\Delta\phi_B$	~20meV/1GPa	Under study Expected small
E_T	↓ w./ stress	↓ w./ stress?

1. **Si: Stress effect on impact ionization rate dominated by mobility enhancement**
   GaN: $\Delta\mu$ and ΔE_G are comparable
2. **Si: Stress modifies barrier height**
   GaN: ?
3. **Si: Stress reduces trap energy level**
   GaN: ?

Traps in Si Devices: Where are the Traps?

Trap activation energy

1.Charge trapping in high – k and/or interface

$E_T(\sigma) < E_T(0) \longrightarrow Q_{ot}(\sigma) < Q_{ot}(0)$

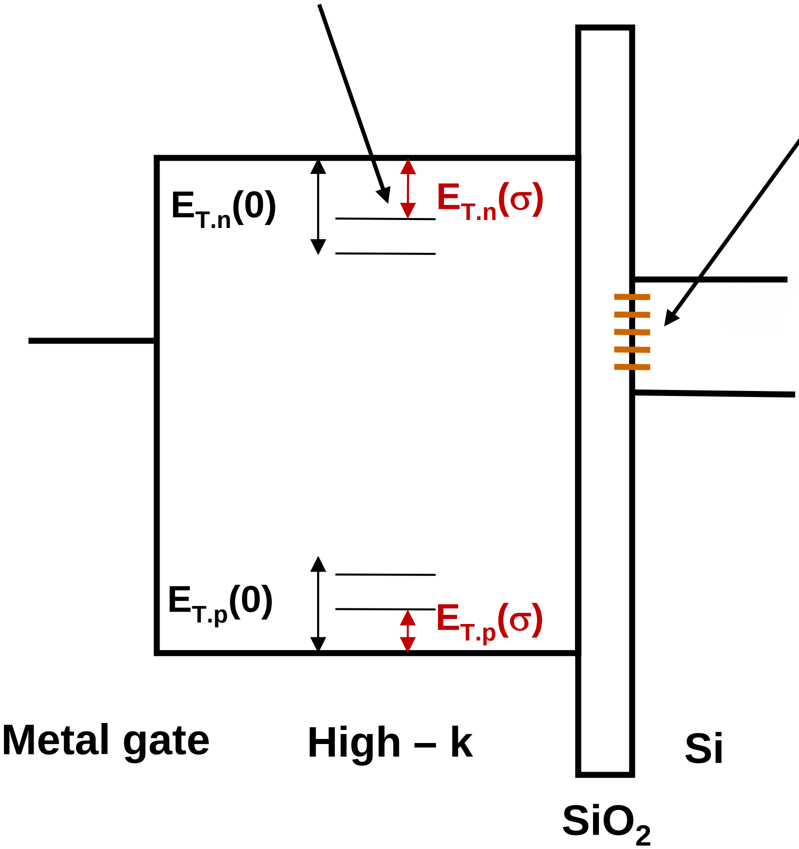
2.Pool-Frenkel Emission

$E_T(\sigma) < E_T(0) \longrightarrow |I_G(\sigma)| > |I_G(0)|$

Interface trap generation

Si – H depassivation under high temperature and/or bias.

$\longrightarrow Qot(\sigma) < Q_{ot}(0)$



APPLIED PHYSICS LETTERS 92, 173507 (2008)

Impact of mechanical stress on direct and trap-assisted gate leakage currents in *p*-type silicon metal-oxide-semiconductor capacitors

Youn Sung Choi, Toshikazu Nishida, and Scott E. Thompson[a]
Department of Electrical and Computer Engineering, University of Florida, Gainesville, Florida 32611, USA

(Received 25 March 2008; accepted 8 April 2008; published online 1 May 2008)

APPLIED PHYSICS LETTERS 93, 153505 (2008)

Strain induced changes in gate leakage current and dielectric constant of nitrided Hf-silicate metal oxide semiconductor capacitors

S. Y. Son,[1] Y. S. Choi,[2,a] P. Kumar,[1] H. W. Park,[2] T. Nishida,[2] R. K. Singh,[1] and S. E. Thompson[2]
[1]*Materials Science and Engineering, University of Florida, Gainesville, Florida 32611, USA*
[2]*Electrical and Computer Engineering, University of Florida, Gainesville, Florida 32611, USA*

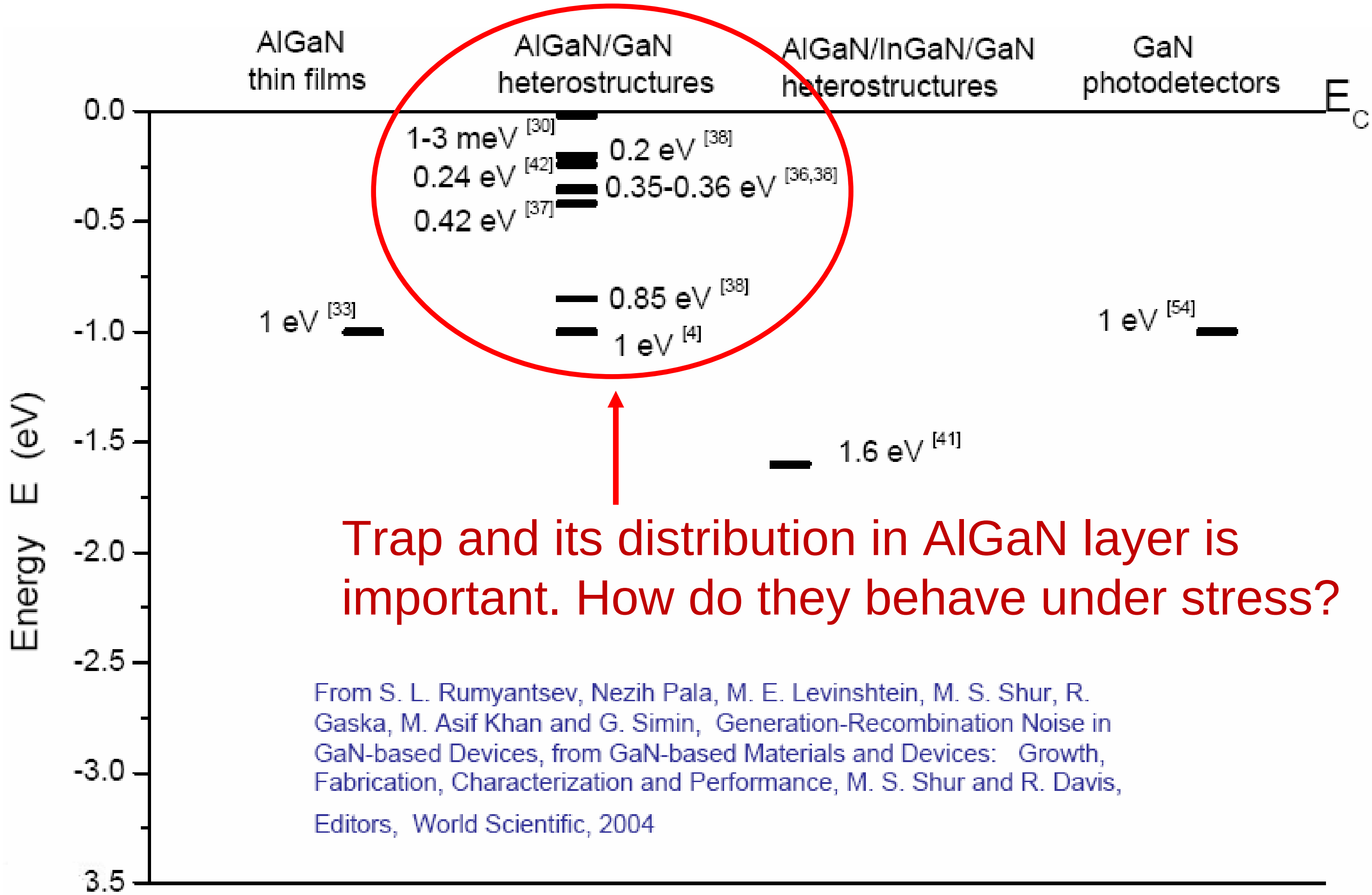
(Received 23 July 2008; accepted 24 September 2008; published online 15 October 2008)

Effect of Uniaxial Mechanical Stress on Gate Induced Drain Leakage Current in Silicon MOSFETs

Toshinori Numata*, Uma Aghoram, Sagar Suthram, Younsung Choi, Ji-Song Lim, Toshikazu Nishida, and Scott E. Thompson [a]

Electrical and Computer Engineering, University of Florida
535 Engineering Building Gainesville FL 32611-6130 USA
Phone: 1(352) 392-8463, Fax: 1(352) 392-8381,
E-mail: [a] thompson@ece.ufl.edu
*On leaving from Toshiba Corporation

Traps in GaN HEMT: Effect of Stress?

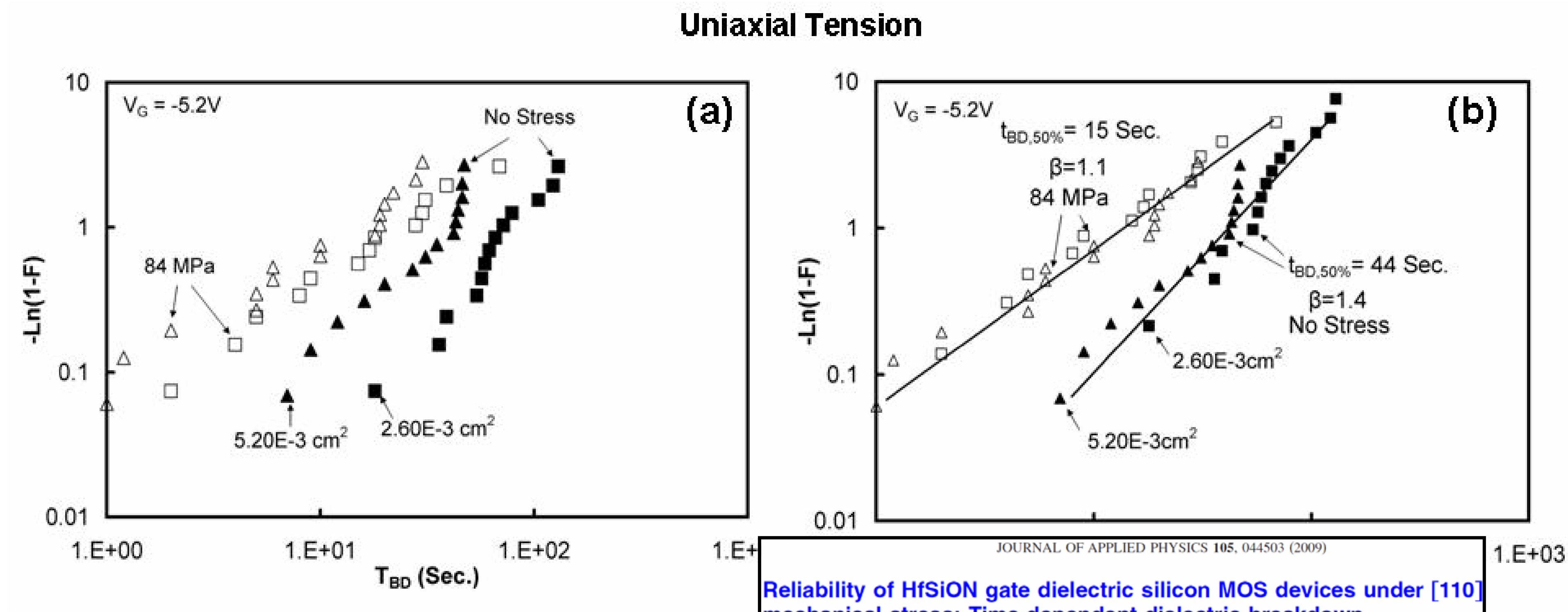


Trap and its distribution in AlGaN layer is important. How do they behave under stress?

From S. L. Rumyantsev, Nezih Pala, M. E. Levinshtein, M. S. Shur, R. Gaska, M. Asif Khan and G. Simin, Generation-Recombination Noise in GaN-based Devices, from GaN-based Materials and Devices: Growth, Fabrication, Characterization and Performance, M. S. Shur and R. Davis, Editors, World Scientific, 2004

Expect: $E_T(\sigma) < E_T(0)$ under mechanical stress

Statistical Study of Stress Effect on TDDB



- **TDDB on Al-gate HfSiON on p-Si MOS capacitor decreases with tensile stress**

JOURNAL OF APPLIED PHYSICS **105**, 044503 (2009)

Reliability of HfSiON gate dielectric silicon MOS devices under [110] mechanical stress: Time dependent dielectric breakdown

Youn Sung Choi,[a] Hyunwoo Park, Toshikazu Nishida, and Scott E. Thompson
Department of Electrical and Computer Engineering, University of Florida, Gainesville, Florida 32611, USA

(Received 12 November 2008; accepted 12 December 2008; published online 19 February 2009)

The time dependent dielectric breakdown (TDDB) of 7–8 nm thick nitrided hafnium silicate (HfSiON) dielectric silicon (Si) metal-oxide-semiconductor capacitors are measured under uniaxial mechanical stress using four point wafer bending along the [110] direction. Both applied tensile and compressive stresses are observed to degrade TDDB. The degradation for both stress polarity is consistent with a previously reported increase in mechanical stress-induced gate leakage via Poole–Frenkel emission. The independence of the charge to breakdown on HfSiON thickness suggests that the degradation under mechanical stress is primary mediated at the HfSiON/Si interface during constant negative gate voltage stressing. © *2009 American Institute of Physics.*
[DOI: 10.1063/1.3074299]

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- Strain in as fabricated devices + inverse piezoelectric strain
- Approach: Characterization as function of systematically applied strain
- Simulation of strain effects on traps and reliability
- Summary

Summary and Characterization Plans

- Goal
  - Employ multiple characterization vectors
  - Gain insight into physical degradation mechanisms
  - Feedback into predictive models
  - Compare predictions with characterization results
- Stress dependence of electrically and optically determined properties of traps
  - Stability of single devices
  - Impact ionization
    - Deformation potentials
- Integration with burn-in, materials analysis, simulation

Acknowledgments

- MURI funding
- Graduate students
  - Min Chu
  - Mehmet Baykan
  - Robert Dieme
  - Amit Gupta
  - Andy Kohler
  - Hemant Rao